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An Experimental Study on Heat Recovery Performances of Three-Dimensional Heat Pipes in Air-Conditioning Systems

Yanqiang Di [1,2,*], Haiyan Di [1,2], Chen Zhao [1,2], Zichen Lu [1,2], Xiaona Li [1,2] and Juan Leng [1,2]

[1] China Academy of Building Research, Beijing 100013, China
[2] China Building Technique Group Co., Ltd., Beijing 100013, China
* Correspondence: yanqiangdi@126.com

Abstract: The applications of conventional heat pipes have been hindered by a few weaknesses, such as the low heat recovery effectiveness, the cross-pollution of fresh and exhaust air, and the difficult switch modes between winter and summer working conditions. In order to find solutions for those problems, a three-dimensional heat pipe exchanger was developed, and an experimental platform was built to test the heat recovery effectiveness of this heat pipe exchanger under different working conditions. Moreover, the operating performances of the three-dimensional heat pipe exchanger unit were monitored throughout one year in a hospital located in the hot summer and cold winter region of China. The field measurement results indicated that the heat recovery effectiveness could be effectively improved by reducing the air volume and the up-wind speed, increasing the cold air and hot air inlet temperature, and increasing the rows of pipes. According to optimizing the structure and operation parameters, the heat recovery efficiencies of the three-dimensional heat pipe exchanger increased by 65~85%. The recommended operation parameters of the three-dimensional heat pipe exchanger in winter and summer for indoor exhaust air temperature were 20 ± 2 °C and 22 ± 2 °C, respectively. The heat recovery effectiveness could reach up to 66% and 64.5% when the indoor and outdoor air temperature differences were higher than 11 °C and 5 °C in winter and summer, respectively. This study provides effective, reliable, and easily implementable methods for the application of three-dimensional heat pipe heat recovery devices in building HVAC systems. It offers guidance for the future design of heat pipe heat recovery devices.

Keywords: exhausted air; heat pipe; operating performance; heat recovery effectiveness; high-efficiency working condition

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1. Introduction

HVAC systems consume 40~60% of the total energy in buildings [1,2]. Therefore, reducing the energy consumption of the air conditioning system plays an important role in energy conservation. Specifically, the fresh air load and exhausted air contributed 20~30% and 30~40% of the total energy consumptions in air conditioning systems. It will inevitably lead to energy waste if the energy is not effectively recycled, thus increase the energy consumption of the air conditioning system. This waste heat could be recycled and supplied to a variety of thermally, mechanically, and electrically driven processes [3]. Relevant studies proved the great potential value of using waste heat in various processes [4,5]. For example, if mechanical ventilation was adopted, the heat loss of the ventilation system in residential buildings could reach up to 35~40 kWh/m^2 [6], 60~95% of which could be recycled by using heat recovery systems [7–9]. Therefore, it is important to recycle and reuse the waste energy in buildings effectively. By using heat recovery systems, the heat loss carried by exhaust air could be converted into recyclable energy, which can reduce the total energy consumption of the air conditioning systems. According to the results concluded by Tanaka and Park [10], 40~50% of the exhausted heat loss was recycled and reused by using a portable generator coupling with a heat pipe. The heat recovery system

could reduce the maximum load of the air conditioning system by pretreating the fresh air, thus reducing the initial investment and the operation costs of the air conditioning systems.

Currently, sensible heat recovery equipment and total heat recovery equipment are commonly employed in air conditioning systems. The heat pipe heat exchanger has several advantages compared with conventional heat recovery equipment, such as low airflow resistance for natural ventilation, the applicability of low-temperature differences, and higher heat transfer rates over small cross-sectional areas [7].

Heat pipes could be effectively applied in various fields of architecture to reduce building energy consumption [11]. Shao et al. [12] analyzed the impacts of heat pipes on the heat and flow losses in pipes, and the results showed that heat pipes could reduce the heat losses effectively. El-Baky and Mohamed [13] found the heat recovery efficiencies of the heat pipe heat exchangers in outdoor air conditioners increased with the rise of inlet fresh air temperature, reached their maximum efficiency of 85%, and the mass flow rates had a significant impact on the variations of fresh air temperature. Ghani et al. [14] explored the application of double-tube heat exchangers in air conditioning systems, and the results indicated that the coefficient of performances (COPs) of the system were improved, and the total energy consumption was reduced. Jouhara and Meskimmon [15] developed a heat pipe heat exchanger to cool the data centers by using outdoor cold air, and 75% of the energy can be conserved. Jouhara and Merchant [16] conducted a study on the thermal recovery efficiency of heat pipe systems under various tilt angles and different thermal load conditions. The research results indicate that by increasing the condenser tilt angle and enhancing the heat transfer thermal load, the efficiency of the heat pipe heat exchanger can be significantly improved. Wang et al. [17] evaluated the performance of a heat recovery ventilator in an indirect evaporative cooling-assisted heat pump, and it covered 60% of the total annual heating/cooling loads with energy efficiency ratios (EER) of 4.5~5. Liu et al. [5] analyzed the energy transfer process of a ventilator with heat recovery and proposed a novel exhaust heat pump ventilator enhanced by a pump-driven loop heat pipe system; the EERs of the composite system were 12.6 in winter and 4.8 in summer, respectively. Huang et al. [18] developed a solar-assisted heat pump water heater by using a heat pipe to enhance the overall performance. The heater operated in a hybrid mode to reduce the building energy consumption, and the average COP under the hybrid operation mode was 3.32, which was 28.7% higher than that of a conventional heat pump system. Han et al. [19,20] proposed an integrated air conditioning system with a gravity-assisted loop heat pipe heat exchanger and evaporative compression system, compared with conventional air conditioning systems, the integrated air conditioning system could save more than 30% of energy consumption.

The traditional heat pipe heat exchangers have the advantages of zero energy consumption, stable working conditions, and effective heat transfer. However, it is limited by several technical aspects, for example, it has to be arranged at a certain angle, and it needs seasonal conversion, as well as inadequate flexibility. As a result, the current heat pipe technologies could not fully meet the increasing demands of heat dissipation. Through a review of relevant literature on the mentioned heat pipes, it is evident that the existed research primarily focused on the impact of heat pipe heat recovery effectiveness in the two-dimensional heat pipe. However, considering more dimensions in heat pipe design, it is possible to reduce the corresponding thermal resistance and enhance practical engineering efficiency. Cheng et al. [21] conducted experiments on a three-dimensional flat pulsating heat pipe with rectangular cross-section channels on both sides. They found that the thermal resistance of the three-dimensional flat pulsating heat pipe depends on input power and operating temperature, with a minimum thermal resistance of only 0.078 °C/W, effectively managing a heat flux density of 86.8 W/cm^2. He et al. [22] introduced series-connected conical nozzles and geometric optimization to promote unidirectional flow in three-dimensional pulsating heat pipes. They studied the impact of fill ratio and heating power on thermal resistance, start-up time, and flow patterns. The results showed that

through geometric optimization on a three-dimensional scale, thermal resistance decreased by 29.5%, and unidirectional flow saw a significant improvement.

In addition, most researchers have focused on traditional heat pipes (2D) to explore their structural parameters, tilt angles, thermal loads, and thermal resistance, with limited studies on the three-dimensionalization of heat pipe structures. To effectively address issues such as low heat recovery effectiveness, cross-contamination in new exhaust air, difficulties in seasonal transitions, and complex installation associated with traditional heat pipes, this paper proposes a three-dimensional heat pipe heat exchanger. As shown in Figure 1, the three-dimensional heat pipe heat exchanger adopts a pipe configuration with a special structure of multiple internal channels, interconnected at both ends, to form a 'three-dimensional thermal circuit' structure. This unique design allows heat to transfer from one side of the three-dimensional heat pipe to the other, including both the front and rear, as well as the upper and lower directions of the pipe rows. In contrast to the design of traditional heat pipes, the breakthrough in the design of the three-dimensional thermal circuit lies in its multiple-row heat pipe configuration. The heat transfer of the working fluid not only depends on the temperature difference between the two sides of the airflow but also relies on the temperature difference between different rows of pipes within the same airflow. This innovative design enables the three-dimensional heat pipe to transmit two to three times the amount of working fluid compared to traditional heat pipes with the same diameter, and the working efficiency of each row of pipes is equal. Therefore, three-dimensional heat pipes have greater heat transfer capacity, occupy relatively less space, and simultaneously reduce air resistance. Compared to traditional heat pipes, the fins and copper tubes of three-dimensional heat pipes, through mechanical or ultra-high-pressure swelling tube systems and persistent pressure testing for leak detection, ensure a tight integration, significantly enhancing heat conduction efficiency. Additionally, the three-dimensional heat pipe can operate with a temperature difference of 1 °C between the evaporator and condenser ends, exhibiting excellent startup characteristics, whereas traditional heat pipes typically require a temperature difference of 8~10 °C for operation.

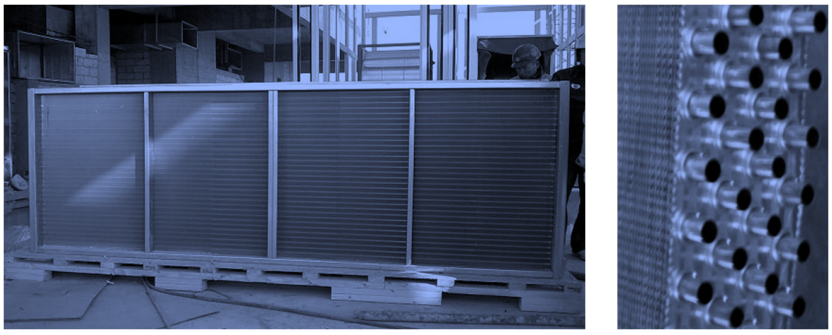


Figure 1. Three-dimensional heat pipe exchanger.

By establishing an experimental platform of the heat pipe heat recovery performance, field measurements were conducted to investigate the thermal performance and heat recovery effect of three-dimensional heat pipe heat exchangers under different working conditions. Furthermore, the three-dimensional heat pipe heat exchanger was applied in a hospital located in the hot summer and cold winter regions of China to explore the appropriate indoor and outdoor temperature differences, the efficiency matching curve, and its high-efficiency working conditions. By searching for efficient heat recovery ranges, the application of three-dimensional heat pipe heat exchangers has been further promoted, contributing to the deepening of research in the field of heat recovery. This provides valuable references for the application of the three-dimensional heat pipe heat exchanger recovery device in the heat recovery aspect of building HVAC systems. It plays a positive role in the design and development of comprehensive and superior-performance heat pipe heat recovery devices.

2. Materials

An experimental platform was established to test the performance of the three-dimensional heat pipe exchanger units under different working conditions. The heat recovery effect of the three-dimensional heat pipe exchanger units was investigated under the variable air volume, indoor and outdoor air temperatures, and the upwind speed.

2.1. Experimental Equipment

The three-dimensional heat pipe heat exchanger unit in this study was composed of a fan box, filter, air inlets and outlets, and the heat pipe heat exchanger. The structure diagram is shown in Figure 2. A middle baffle was placed in the center of the box of the three-dimensional heat pipe heat exchanger unit to separate the box into two parts, namely the exhaust air side and the fresh air side. Indoor air is sequentially expelled outdoors through the filter, three-dimensional heat pipe, and fan, while fresh air passes through the filter, three-dimensional heat pipe, coil (cooling/heating), humidifier, and fan to meet indoor environmental requirements before entering the room. The center of the box body was composed of a three-dimensional heat pipe heat exchanger passing through the middle baffle, and a condensation pan was installed at the bottom of the three-dimensional heat pipe heat exchanger.

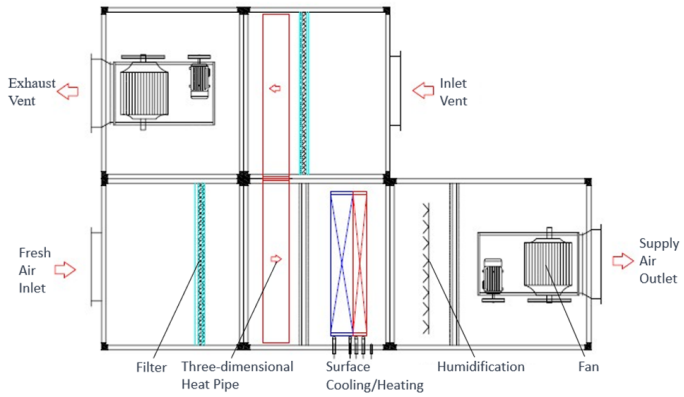


Figure 2. Three-dimensional heat pipe energy recovery air conditioning unit.

In this experiment, 3 three-dimensional heat pipe heat exchange units with different air volumes were used, and their structural diagrams are shown in Figure 3.

The above three types of three-dimensional heat pipe heat exchangers all contain a serpentine heat pipe, which has multiple serpentine coils. The adjacent coils have opposite openings and are connected by U-shaped bends to form a simple serpentine heat pipe. These pipes are filled with an appropriate amount of refrigerant. The refrigerant, relying on the internal pressure of the pipes and the temperature difference outside the pipes, continuously flows within the serpentine coils. Fins are installed on the serpentine pipes to enhance the heat transfer capability, forming a serpentine heat pipe heat exchanger. The three-dimensional heat pipe serpentine structure is illustrated in Figure 4. The heat exchanger comprised a continuous closed-loop pipeline, where the first segment of the non-serpentine straight pipe serves as the evaporating section, the second segment functions as the condensing section, and they are separated by an adiabatic section. During operation, a portion of the refrigerant flows in a separate non-serpentine straight pipe, while the remaining refrigerant circulates within the straight pipe inside the serpentine coil in the traditional heat pipe manner. The first and second segments in this continuous closed loop can be part of the serpentine pipeline or exist as independent components of the serpentine pipeline.

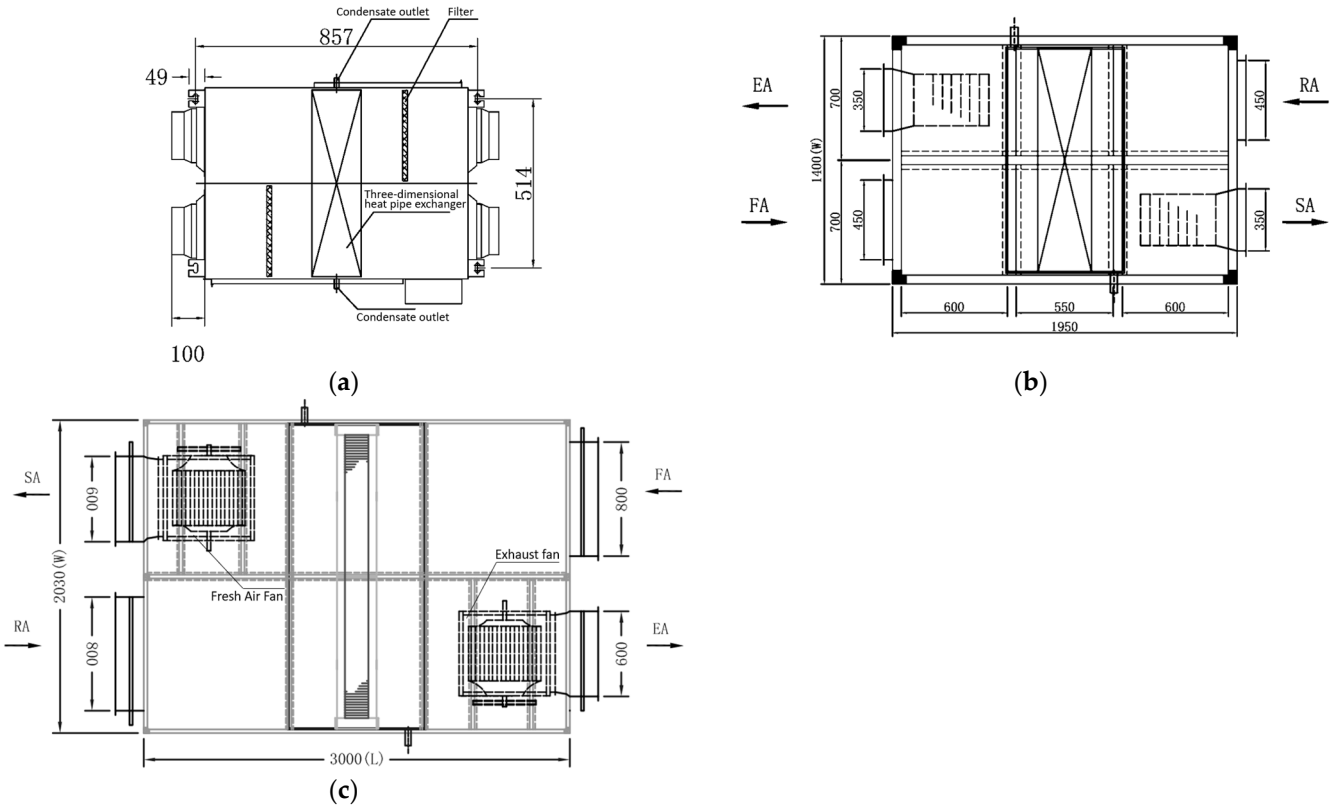


Figure 3. Three-dimensional heat pipe exchanger unit with an air volume of 100 m^3/h (**a**), 1000 m^3/h (**b**), and 10,000 m^3/h (**c**).

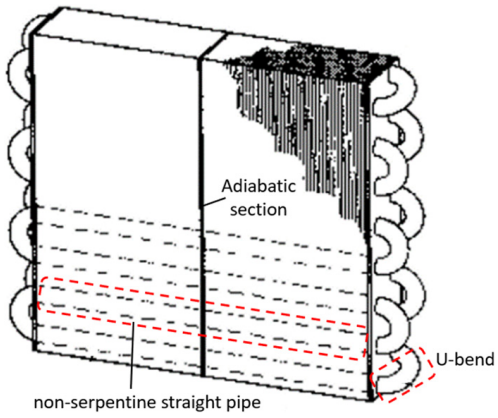


Figure 4. The snake structure diagram of the three-dimensional heat pipe.

The basic parameters of the 3 three-dimensional heat pipe exchanger units are given in Table 1.

Before conducting the vacuuming and filling experiments on the three-dimensional heat pipe heat exchanger, it is essential to carefully clean and leak-test each component. Such procedures aim to ensure that the working fluid fully wets the pipe walls, preventing the release of non-condensing gases due to impurities and contaminants and thereby avoiding compromising the vacuum level of the pipeline.

Table 1. Three-dimensional heat pipe exchanger unit with air volume of 100 m^3/h, 1000 m^3/h, and 10,000 m^3/h.

Contents		Parameters		
Equipment Model		**HPQS-100**	**HPQW-01**	**HPQW-10**
Supply air fan	Air volume	100 m^3/h	1000 m^3/h	10,000 m^3/h
	Fan static pressure	13 Pa	150 Pa	330 Pa
	External static pressure	100 Pa	100 Pa	100 Pa
Exhaust air fan	Air volume	100 m^3/h	1000 m^3/h	10,000 m^3/h
	Fan static pressure	15 Pa	150 Pa	330 Pa
	External static pressure	100 Pa	100 Pa	100 Pa
Water collection plate	Material	Stainless steel plate		
	Pipe diameter	2-DN25		
Box body and Insulation	Wall insulation thickness	25 mm		
	Wall material	Galvanized sheet/colored steel plate		

2.2. Experimental Settings

The experimental settings are illustrated in Figure 5. The environment chamber was composed of a hot environment room and a cold environment room, with indoor temperatures maintained at 30~40 °C and 20~30 °C, respectively. The experimental setup in the indoor environmental chamber consists of a three-dimensional heat pipe heat recovery unit, cooling device, heating device, thermocouples, and other components.

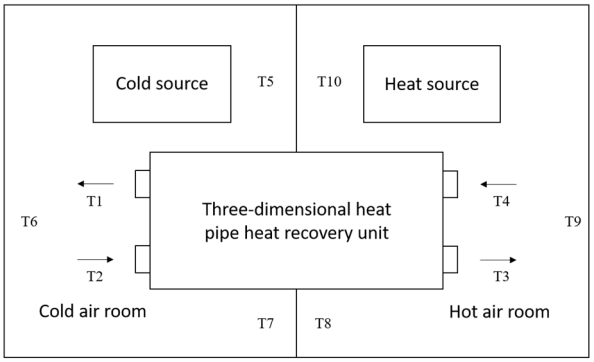


Figure 5. Environment chamber for the test of the three-dimensional heat pipe exchanger unit.

In order to create the test environment, the air conditioner was used as the cold source for cooling, while the air heater was used as the heat source for heating. Under the cooling condition, the outdoor supply air inlet parameters of the exhaust air heat recovery device were selected as the inlet parameters in the summer condition. Under the heating conditions, the air heater that had 3 power levels and wind speed levels was used to provide indoor environment control.

2.3. Measuring Positions

The actual layout of the environment chamber and three-dimensional heat pipe exchanger unit are shown in Figure 6.

The measuring positions included the cold air inlet temperature T2, the cold air outlet temperature T1, the hot air inlet temperature T4, the hot air outlet temperature T3, the cold air chamber temperature measuring points (T5, T6, T7), and the hot air chamber temperature measuring points (T8, T9, T10), 10 temperature measuring positions in total.

The temperature monitoring positions are located at four tuyeres of the inlet and outlet duct. The t-type thermocouples with protective probes were selected for temperature, the measurement range of which was −40~350 °C, and the accuracy was ±0.1 °C. The air temperature data were collected continuously.



(**a**) (**b**) (**c**)

Figure 6. Layout of the experimental platform. (**a**) Construction and assembly of the three-dimensional heat pipe heat recovery unit; (**b**) Layout of the environmental chamber for the three-dimensional heat pipe heat recovery unit; (**c**) Real installation scene of the three-dimensional heat pipe heat recovery unit.

3. Results and Discussions

The optimal operating conditions for heat pipe heat exchanger design are subject to several heat transfer limitations, which determine the maximum achievable heat transfer rate of a specific design under certain operating conditions [13].

3.1. Thermal Performance Analysis under Different Conditions

3.1.1. Effects of the Variations in the Air Volume

The effects of the air volume of the three-dimensional heat pipe exchanger unit on the heat recovery effectiveness were investigated in this study. During the test, the cold air inlet temperature T2 was 24 °C, and the hot air inlet temperature T4 was 34 °C. The fresh air volume was 100 m^3/h, 1000 m^3/h, 10,000 m^3/h, respectively.

The effectiveness of a heat exchanger is defined as the ratio of the actual heat transfer rate of the heat exchanger to the maximum possible heat transfer rate between the two streams of air [23]. According to Equation (1), the heat recovery effectiveness of the heat pipe could be obtained. The results were illustrated in Figure 7, and the accuracy of heat recovery effectiveness was set as 0.01.

$$\varphi = \frac{T4 - T3}{T4 - T2} \quad (1)$$

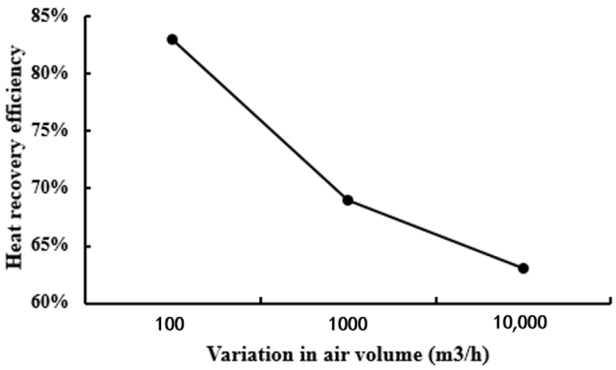


Figure 7. Changes in heat recovery effectiveness under different air volumes.

The results showed that the heat recovery effectiveness of the three-dimensional heat pipe exchanger unit reduced gradually as the air volume increased. The heat recovery effectiveness was 83% when the air volume was 100 m^3/h. When the air volume was 1000 m^3/h, the heat recovery effectiveness was 69%. When the air volume increased to 10,000 m^3/h, however, the heat recovery effectiveness reduced to 63%. This is consistent with the findings of Lin et al. [24], who utilized Computational Fluid Dynamics (CFD)

simulations to assess the heat recovery performance of heat pipes, confirming that heat transfer within the heat pipe decreases with an increase in flow rate. The potential reason lay in the fact that the increase in air volume meant the increase of heat, leading to the increase of the outlet temperature T3. According to Equation (1), the heat recovery effectiveness decreases when other temperatures remain constant.

3.1.2. Effects of the Variations in the Cold Air Inlet Temperature

When the hot air inlet temperature T4 was 34 °C, and the air volume was 1000 m^3/h, the heat recovery effectiveness of the three-dimensional heat pipe exchanger unit was scrutinized at different cold air inlet temperatures. When testing with a hot air inlet temperature (T4) of 34 °C and cold air inlet temperatures of 22 °C, 24 °C, 26 °C, and 28 °C, the exit temperature of the hot air (T3) was recorded. The heat recovery effectiveness can be calculated using Equation (1). The detailed results are given in Figure 8.

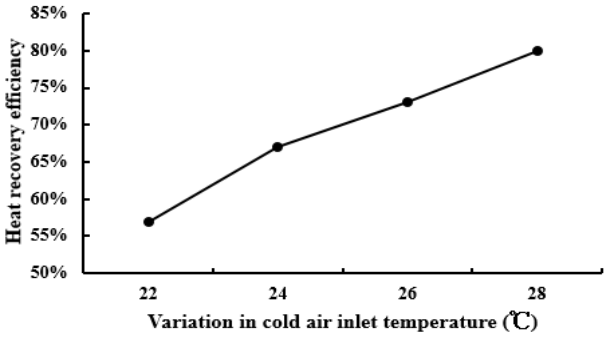


Figure 8. Changes in heat recovery effectiveness under different cold air inlet temperatures.

The results showed that results showed that the cold air inlet temperature would result in different heat recovery effectiveness. As illustrated in Figure 8, when the outdoor temperature was stable, changes in the indoor air temperature would bring changes in the heat recovery effectiveness. In terms of Equation (1), the heat recovery effectiveness was determined by the temperature differences between the inlet and outlet of hot air, as well as the indoor and outdoor air temperature differences. The inlet hot air temperature was the outdoor temperature. Research by El-Baky and Mohamed [13] found that heat recovery effectiveness improved when the inlet temperature of fresh air increased. Moreover, when the inlet temperature of fresh air was raised to 40 °C, the efficiency of the condenser and evaporator sections also increased accordingly. The enthalpy ratio of heat recovery and conventional air mixing increased by approximately 85%. This means that the higher the outdoor temperature, the stronger the evaporation effect would be. On the contrary, when the indoor temperature increased, the difference between indoor and outdoor air temperatures reduced. As a result, the heat recovery effectiveness increased. Therefore, the heat recovery effectiveness of the three-dimensional heat pipe exchanger unit could be improved by increasing the indoor air temperature within appropriate ranges.

3.1.3. Effects of the Variations in the Hot Air Inlet Temperature

When the cold air inlet temperature T2 was 24 °C, and the air volume was 1000 m^3/h, the cold air inlet temperature T4 was used to test the heat recovery effectiveness of the three-dimensional heat pipe exchanger unit. When the cold air inlet temperature T2 was 24 °C and the hot air inlet temperature was 30 °C, 34 °C, 38 °C, and 40 °C respectively, the hot air outlet temperature T3 was recorded. Then, the heat recovery effectiveness could be calculated according to the heat recovery effectiveness formula Equation (1). The results are shown in Figure 9.

As illustrated in Figure 9, the heat recovery effectiveness increased as the hot air inlet temperature elevated. When the hot air inlet temperature was 30 °C, the efficiency reached the minimal level of 54%. When the hot air inlet temperature was 40 °C, the efficiency

reached the peak value of 77%, which indicated that the higher the hot air inlet temperature, the better the heat transfer and the higher the heat recovery effectiveness.

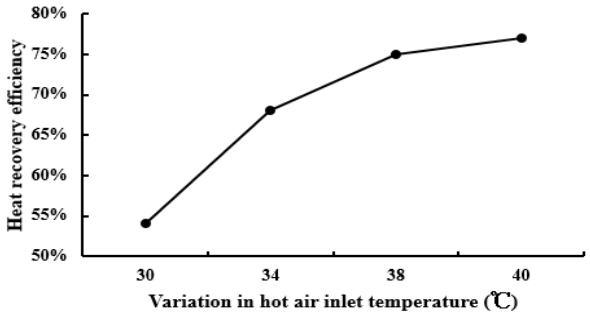


Figure 9. Variations of heat recovery effectiveness under different hot air inlet temperatures.

3.1.4. Effects of the Variations in the Upwind Speed

When the cold air inlet temperature T2 was 24 °C, and the hot air inlet temperature T4 was 34 °C, the air volume was 1000 m^3/h, and the row numbers of the tube were 2, 4, 6, and 8, respectively, the heat recovery effectiveness of the three-dimensional heat pipe exchanger unit was tested under different the upwind speed. In the experiment, the upwind speed was controlled by the digital control inverter. The results of recording and processing the data are shown in Figure 10.

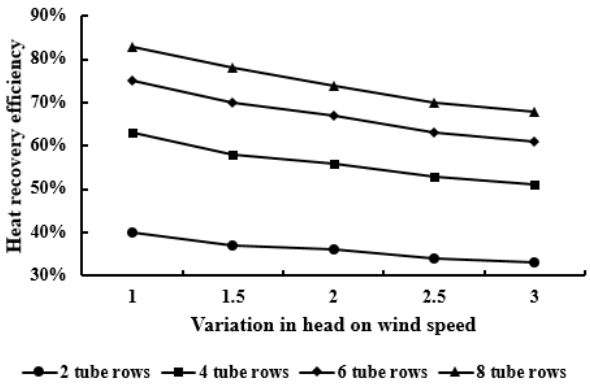


Figure 10. Changes in heat recovery effectiveness under different upwind speeds.

Figure 10 revealed that the heat recovery effectiveness of three-dimensional heat pipes reduced as the upwind speed increased but increased as the number of tube rows increased. Taking the upwind speed of 2.5 m/s, for example, when the number of tube rows increases from 2 to 8, the heat recovery effectiveness increases from 34% to 70%. This trend is also supported by the research findings of Meena et al. [25]; within a certain range, the heat transfer rate and heat transfer efficiency gradually decrease as the hot air velocity increases. This was owing to the fact that the contact area between air and the three-dimensional heat pipe exchanger increased as the number of tube rows increased. Therefore, the heat exchange rate increased, and the heat recovery effectiveness became higher. On the contrary, the smaller the number of tube rows, the smaller the contact area between fresh air and heat pipe, leading to a lower heat exchange capacity and, thus, a lower heat recovery effectiveness.

Furthermore, taking six rows of pipes as an example, the upwind speed increased from 1.0 m/s to 3.0 m/s, and the heat recovery effectiveness decreased from 75% to 61%. A lower change rate of efficiency was observed when the upwind speed was greater than 2.5 m/s. The possible reason lay in that as the upwind speed increased, the contact time of the air decreased; thus, the heat exchange was less efficient, promoting a decrease in cooling efficiency and leading to attenuated heat recovery effectiveness [26]. Although the

wind speed kept increasing, little impact on heat exchange was observed. On the contrary, the lower the upwind speed, the longer the contact time between the fresh air and the three-dimensional heat pipe exchanger, leading to a heat exchange rate and the greater the temperature differences between the inlet and outlet of the fresh air side, which further resulted in higher efficiency of the three-dimensional heat pipe exchanger.

In practical applications, the heat recycled by the equipment was also an important factor to consider. The lower the upwind speed, the higher the temperature differences between inlet and outlet air, and the higher the heat recovery effectiveness, but the air flow rate through the three-dimensional heat pipe exchanger is reduced. On the contrary, as the air velocity increased, the temperature differences between inlet and outlet air decreased. Thus, the heat recovery effectiveness decreased, but the air flowing through the three-dimensional heat pipe exchanger increased. In comparison, the heat recovered was not the same. Therefore, analysis should be conducted based on the specific conditions in real settings.

3.2. Indoor and Outdoor Temperature Difference (Time)—Efficiency Matching Curve

In practical applications, it is usually hard to evaluate the energy conservation and economic benefits of the energy recycling unit. Temperature efficiency is a commonly used indicator to evaluate the heat transfer performance of heat recovery units. However, the operating conditions of units vary greatly throughout the year since the outdoor air temperature varies from −5 °C to 38 °C, leading to a 10% efficiency fluctuation.

According to the analysis in Section 3.1, the heat recycling efficiency of the three-dimensional heat pipe exchanger unit was usually affected by indoor and outdoor air temperature during the operation process both in winter and summer. To further investigate this influencing factor, in this section, 1-year performance data of the three-dimensional heat pipe exchanger unit that was used in a hospital in hot summer and cold winter areas was analyzed to find the most efficient working interval of the three-dimensional heat pipe exchanger, under different operating conditions in winter and summer. In addition, the relationship between heat recovery effectiveness and indoor/outdoor temperature was also investigated. The schematic diagram of the three-dimensional heat pipe heat recovery unit is shown in Figure 11. During the winter, the unit recovers heat from warm indoor exhaust air and transfers it to the fresh air for effective utilization. In the summer, the unit transfers the coolness from indoor exhaust air to fresh air, achieving heat recovery for the three-dimensional heat pipe heat exchanger.

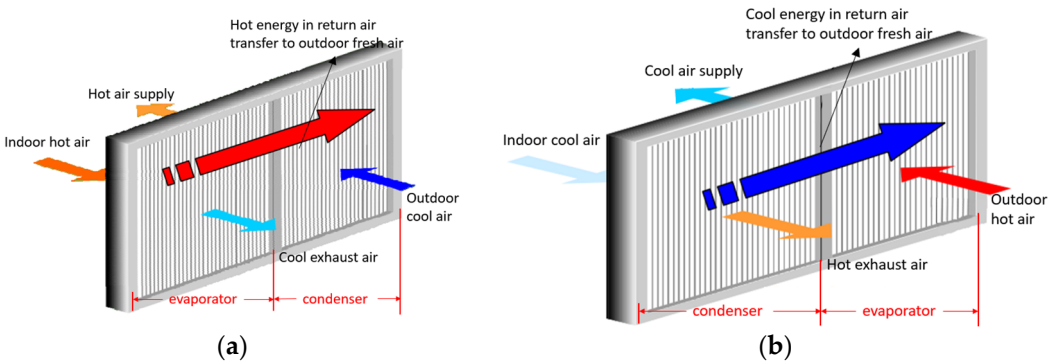


Figure 11. Schematic Diagram of the Three-Dimensional Heat Pipe: (**a**) Winter Operation; (**b**) Summer Operation.

During the one-year measurement, the fresh air volume was 3000 m^3/h, the exhaust air temperature was about 26 °C in summer, and the maximum fresh air temperature was 38 °C. In winter, the exhaust air temperature was about 18 °C, and the minimum fresh air temperature was −5 °C.

The operating time of the heat recovery system of the three-dimensional heat pipe exchanger unit was the same as that of the air conditioning system. When the outdoor air temperature was lower than the designed indoor air temperature in winter, the equipment switched to the winter operation mode. On the contrary, if the outdoor air temperature was higher than the designed indoor air temperature in summer, the device would switch to the summer operation mode. Except for these two conditions, the bypass mode was switched on in other seasons.

3.2.1. Relationship between Indoor/Outdoor Temperature Differences and the Heat Recovery Effectiveness under Winter Conditions

Considering the fluctuation in the exhaust air temperature of the winter air-conditioning system within the range of 10~24 °C, the exhaust temperature (indoor temperature) of the three-dimensional heat pipe was set at 14 °C, 16 °C, 18 °C, and 20 °C. Taking into account a fluctuation of 2 °C, these were designated as working conditions 1, 2, 3, and 4, respectively.

The influence of indoor and outdoor temperature differences on the heat recovery effectiveness under different working conditions in winter is illustrated in Figure 12. As indicated in Figure 12, the heat recovery effectiveness increased rapidly and then tended to remain stable when the difference in indoor and outdoor air temperature increased from 3 °C to 9.5 °C. In addition, the heat recovery effectiveness under low-temperature conditions (Condition 1 and Condition 2) was higher than that under higher-temperature conditions (Condition 3 and Condition 4). When the indoor and outdoor air temperature difference increased from 11 °C to 14 °C, the heat recovery effectiveness was reduced under low-temperature conditions (Condition 1 and Condition 2), while under higher temperature conditions (Condition 3 and Condition 4), the heat recovery effectivenesses increased firstly then reduced slightly, and the heat recovery effectiveness was higher under higher temperature conditions. The reasons for these changes were mainly ascribed to the low-temperature working conditions and the high liquid phase mass transfer coefficient of the medium in the tube, leading to a good heat transfer performance. However, as the indoor and outdoor air temperature difference was higher than 11 °C, the effects of the increased temperature difference of the heat transfer process on the heat recovery performance were significant, which would bring an improved temperature efficiency, although it was also influenced by the liquid phase mass transfer coefficient of the working medium.

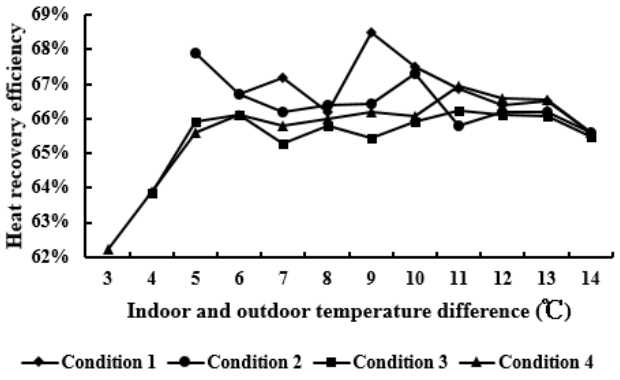


Figure 12. Influences of indoor and outdoor air temperature difference on heat recovery effectiveness under different working conditions in winter.

3.2.2. Relationship between Indoor/Outdoor Temperature Difference and Heat Recovery Effectiveness under Summer Conditions

Considering the fluctuation in the exhaust air temperature of the summer air-conditioning system within the range of 20~30 °C, the exhaust temperature (indoor temperature) of the three-dimensional heat pipe was set at 22 °C, 24 °C, and 26 °C. Taking into account a fluctuation of 2 °C, these were designated as working conditions 1, 2, and 3, respectively.

The influence of indoor and outdoor temperature differences on the heat recovery effectiveness under three different working conditions in summer was illustrated in Figure 13. As indicated in Figure 13, the heat recovery effectiveness reduced slightly at first but then increased as the indoor and outdoor temperature difference increased, and higher heat recovery effectiveness was observed under high-temperature conditions.

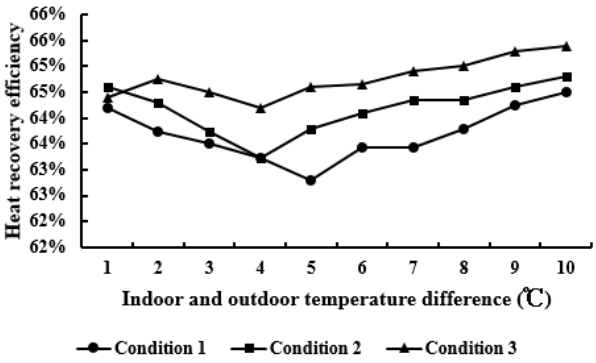


Figure 13. Influences of indoor and outdoor air temperature difference on heat recovery effectiveness under different working conditions in summer.

It was also observed that the heat recovery effectivenesses in summer had a greater fluctuation than that in winter, the possible reason for which was that the thermal resistance of the working medium during the evaporation was higher than that during the condensation process, leading to greater changes of the heat transfer process thus better heat recovery effectivenesses. Furthermore, it corroborates the findings of Obeida et al. [27], who conducted a comparative analysis of heat transfer capacity, temperature effectiveness, and heat recovery effectiveness of heat pipes during winter and summer operating conditions, demonstrating that the performance of heat pipes is relatively superior in winter.

3.3. High-Efficiency Working Conditions

3.3.1. Winter Condition

Figure 12 revealed that the heat recovery effectiveness increased as the differences in indoor and outdoor air temperatures rose. Specifically, significant changes in the heat recovery effectiveness were observed when the air temperature difference was less than 6 °C. When the difference in air temperature increased from 6 °C to 11 °C, the heat recovery effectiveness under different working conditions exhibited irregular patterns. When the difference between indoor and outdoor air temperatures was greater than 11 °C, however, the heat recovery effectiveness became stable.

Meanwhile, comparisons among these four working conditions indicated that the three-dimensional heat pipe produced the highest heat recovery effectiveness under Condition 4. Therefore, the recommended operation condition was Condition 4 in winter, and higher performance would appear when the indoor and outdoor air temperature difference was greater than 11 °C.

3.3.2. Summer Condition

Figure 13 revealed that the heat recovery effectivenesses had an overall increase as the indoor and outdoor air temperature difference elevated. Specifically, a slight reduction of the heat recovery effectiveness was observed when the air temperature difference was less than 5 °C. However, when the difference in air temperature was above 5 °C, the heat recovery effectiveness under different working conditions was elevated.

By comparing the changes in the heat recovery effectiveness under these three working conditions, it was found that Condition 3 corresponded to the highest heat recovery effectiveness. Therefore, Condition 3 was the recommended operation condition for the

summer condition. Higher performance would appear when the difference in indoor and outdoor air temperature was greater than 5 °C.

4. Conclusions

The thermal performance and heat recovery effectiveness of the three-dimensional heat pipe exchanger were investigated experimentally under different working conditions. The relationship between the indoor/outdoor air temperature difference (time) and the heat-recovery efficiency, as well as the high-efficiency working conditions of the three-dimensional heat pipe heat exchangers, were obtained. The main findings were provided as follows:

(1) At a condition with a cold air inlet temperature of 24 °C and a hot air inlet temperature of 34 °C, under a temperature difference of 10 °C between the cold and hot inlets, the heat recovery effectiveness exhibited variations at different airflow rates. The heat recovery rates were 0.83, 0.69, and 0.63 when the air volume was 100 m^3/h, 1000 m^3/h, and 10,000 m^3/h, respectively.

(2) When the cold air inlet temperature was 22 °Cand 28 °C, the heat recovery effectiveness was 57% and 80%, respectively. To a certain extent, the heat recovery effectiveness could be improved by increasing the indoor air temperature.

(3) Elevation of the hot air inlet temperature produced gradual increases in the heat recovery effectiveness of the three-dimensional heat pipe exchanger unit. The lowest heat recovery effectiveness (54%) was observed at the hot air temperature of 30 °C, while the highest heat recovery effectiveness (77%) was observed at the hot air temperature of 40 °C.

(4) The heat recovery effectiveness of the three-dimensional heat pipe decreased with the increasing oncoming wind speed but showed an increasing trend with the increase in the number of pipe rows. Taking an oncoming wind speed of 2.5 m/s as an example, as the number of pipe rows increased from 2 to 8, the heat recovery effectiveness rose from 34% to 70%. For six rows of pipes, as the oncoming wind speed increased from 1.0 m/s to 3.0 m/s, the heat recovery effectiveness decreased from 75% to 61%. When the oncoming wind speed exceeded 2.5 m/s, the temperature efficiency change tended to be more gradual.

(5) The recommended high-performance operation conditions in winter and summer were investigated. At the indoor exhausted air temperature of 20 ± 2 °C and the indoor and outdoor air temperature difference over 11 °C, the higher heat recovery effectiveness in winter was obtained. In summer, however, the high performance occurred at the exhausted air temperature of 22 ± 2 °Cand the indoor and outdoor air temperature difference over 5 °C.

Through experimental testing, the performances of the three-dimensional heat pipe heat exchanger under different operating conditions were evaluated. The results indicated that it had better thermal performance and heat recovery effectiveness compared with traditional heat pipe exchangers. Field experiments focused solely on studying the thermal performance of the three-dimensional heat pipe under varying airflows, different temperatures of incoming cold and hot air, and different face velocities. By examining factors such as indoor/outdoor temperature differentials and heat recovery effectiveness, a range suitable for efficient operation was determined. Therefore, in future research, it is essential to delve into the comprehensive effects of various factors to gain a more thorough understanding of the performance of the three-dimensional heat pipe heat exchanger. This includes but is not limited to, comprehensive studies on different climatic conditions, variations in system loads, and the stability of equipment operation. Such in-depth research will contribute to better system design optimization, enhancing the adaptability of the system to diverse operating conditions and further improving thermal performance and heat recovery effectiveness. The outcomes of these studies will provide more practical and reliable design guidance for heat recovery devices in future building HVAC systems, aiming to achieve more sustainable and efficient energy utilization.

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